Mr Hacking

NATION SHALL SPEAK PEACE UNTO NATION

RESEARCH DEPARTMENT

A photo-electric lens-testing bench

REPORT No. T·108

1963/20

THE BRITISH BROADCASTING CORPORATION
ENGINEERING DIVISION

RESEARCH DEPARTMENT

A PHOTO-ELECTRIC LENS-TESTING BENCH

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SUMMARY

A photo-electric lens test bench capable of measuring lenses of focal length from 12 mm to 1 m is described. Designed specifically for television applications, it gives the "optical transfer" curve automatically plotted on recording paper, using the sine-wave analyser described by Hacking. Facility is also provided for the recording of the "spread function". The angular field is somewhat in excess of $\pm 45^\circ$; the field diagonal in the image plane is limited to $\pm$ 100 mm. An air-spaced doublet of 3·05 m focal length and 200 mm diameter is used as collimator.

Provision is made for the measurement of the optical transfer function for imagery at finite conjugates by the addition of a second cross-slide with its own light source and test object. The bench is physically large enough to accommodate large zoom lenses and complete optical systems.

Some comparisons of two basic types of optical bench are given and the accuracy of the final result is discussed.

1. INTRODUCTION

The optical bench was designed and constructed so that accurate measurement of the modulation transfer characteristic of any lens likely to be used by the Television Service could be made. Prior to the installation of this bench in January 1960, measurements of modulation transfer characteristics were made on a modified version of the Mark 1 Taylor Hobson Optical Bench.[1] A serious limitation of this bench was its inability to measure lenses of focal length in excess of 6 in (150 mm). Further, the measurement of lenses at finite conjugates was not easy with this particular bench as it was intended primarily for working with a test object at infinity.

In designing a new and larger optical bench, it was desirable that these two limitations should be overcome and the attempt was made to design a bench suitable for all optical measurements (of modulation transfer characteristic) relevant to television. These include complete optical systems and zoom lenses in addition to fixed-focus single lenses.

2. REQUIREMENTS

2.1. For a Single Lens

Focal length range	from ½ in to 40 in (12·7 to 1016 mm)
Aperture	f/1·0 to f/16
Semi-angular field	not less than 40°
Spatial frequencies	normally from zero up to about 30 c/mm (occasionally up to 60 c/mm)
Object distance	either infinite or finite as application demands.

2.2. For Zoom Lens

In addition to measuring the modulation transfer characteristic for a range of focal lengths from 12 mm to 1 m, the minimum working distance for accurate zooming should be easy to check.

2.3. For Optical Systems

Sufficient space should be available to install and measure complete systems such as colour-camera optical systems and multiplex telecine optics.

3. METHODS OF MEASUREMENT OF THE OPTICAL TRANSFER FUNCTION*

Prior to 1960, the standard method of determining the optical transfer function in Research Department was by means of the "spread function". This was recorded automatically[2] and a Fourier transform of the spread function was obtained by a sampling method using a desk-calculator.[3] This method was adequate for our purposes but suffered one grave disadvantage, namely that the process of sampling the spread function and then doing the computation on the desk-calculator was very time-consuming.

In 1958, Hacking[4] suggested a method, based on an optical Fourier transform generator originally described by Born et al,[5] in which the Fourier transform is obtained directly from the spread function. It was decided that the new optical bench should provide for the use of this method as well as the older method.

4. SINE-WAVE ANALYSER

It may be appropriate at this point to explain how the sine-wave analyser performs the Fourier transform of the spread function. The lens under test forms an image of a thin slit test-object and this image is magnified by a microscope objective.

*Optical transfer function is the name recommended by the International Commission for Optics for frequency response when both phase and amplitude are considered. The modulus of this is to be called "modulation transfer function".

The magnified image is made coplanar with a thin slit which is oriented at right angles to the image of the test object slit. The thin slit thus takes a representative sample of the magnified image. Immediately behind this thin slit is a photographic plate which has a sinusoidal variation of transmission (sine-wave grating). The spread function is thus multiplied by a sinusoid and the transmitted light flux is then allowed to fall on the photocathode of a photomultiplier where integration takes place, the current flowing in the photomultiplier being directly proportional to

$$\int_{-A}^{A} f(x) \cos (\omega x + \delta) \, dx + C$$

where $f(x)$ is the spread function

$\omega/2\pi$ is the spatial frequency of the sinusoid (as seen through the thin slit)

δ is an arbitrary phase angle depending on the setting of the sinusoid vis-a-vis $f(x)$

$2A$ is the length of the thin slit (near to the sinusoid)

C is a constant depending on the mean transmission of the sine-wave plate.

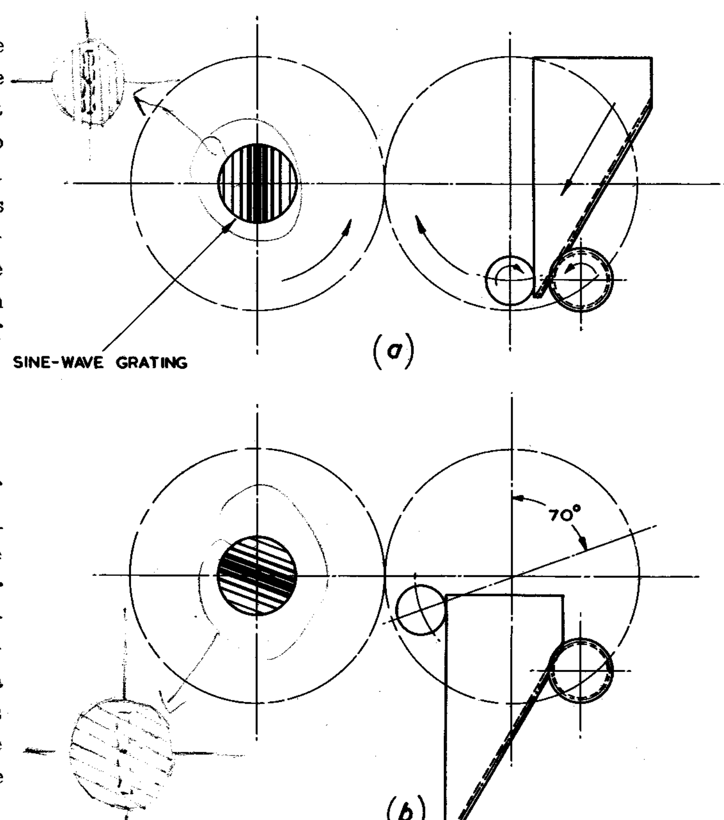


Fig. 1 - Mechanical coupling used with sine-wave analyser

(a) Beginning of the recording cycle

(b) End of the recording cycle

The spatial frequency $\omega/2\pi$ can be changed by causing the sine-wave plate to rotate. If the lines of constant transmission are initially parallel to the thin slit, the effective spatial frequency will be zero; when the lines of constant transmission are perpendicular to the thin slit, then the spatial frequency will be a maximum (f_0) and for intermediate values of rotational angle θ we have

$$f = f_0 \sin \theta$$

In the mechanical drive of the sine-wave plate, a mechanical coupling (Fig. 1) is used so that the frequency scale on the recording paper shall be linear rather than one depending on the sine of the angle of rotation. In the present equipment a rotation of 70° is employed. This gives over 90% of the maximum possible frequency range of the sine-wave plate.

Two settings of the phase of the sine-wave plate with reference to the adjacent thin slit are usually necessary for the complete Fourier

transform; the cosine component* is obtained with the sine-wave plate adjusted to obtain the maximum photocurrent. It may be shown that the sine component is obtained by a lateral shift of the sine-wave plate such that the photocurrent corresponds to the mean transmission of the sine-wave plate. It is essential that as the sine-wave plate rotates, a constant phase position (e.g. a maximum) be maintained at the centre of the slit. The mathematical process involved in these two operations is illustrated in Figs. 2(a) and 2(b). The only difference between the mathematical process and the method used in the sine-wave analyser arises because the sinusoidal plate has a non-zero mean level, but this is trivial and can easily be allowed for. The modulus of the optical-transfer function is the root sum of the squares of the sine and cosine components.

5. BASIC DESIGN

The optical bench used up to 1960 was an adaptation of a Mark 1 Taylor Hobson Bench[1] and was of the nodal-slide type. This means that the lens is mounted on a turntable and adjustment is provided so that the rear nodal point of the lens under test can be brought into coincidence with the axis of rotation of the turntable. Under these conditions the image suffers no lateral movement when the turntable is rotated. The provision of a tee-bar makes automatic adjustment for the increase in back-working-distance for off-axis imagery. Figs. 3(a) and 3(b) show diagrammatically the operation of this type of bench.

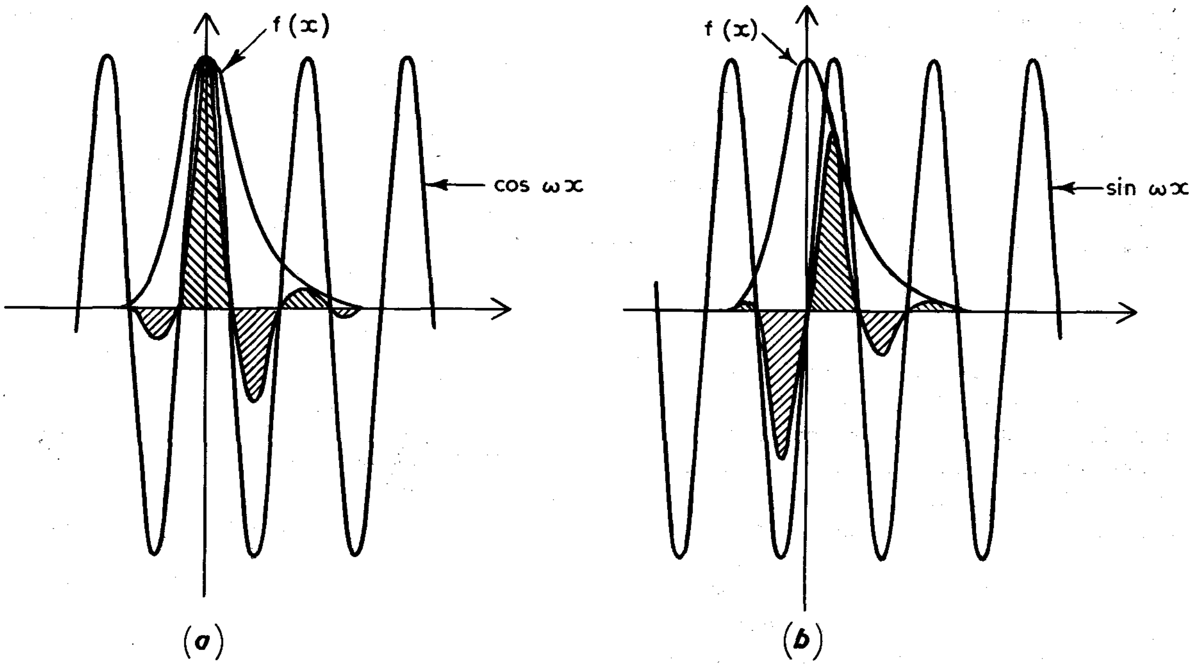
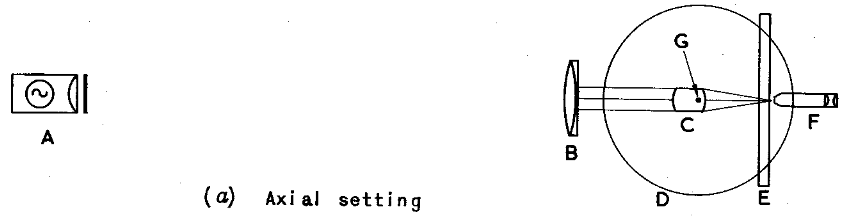


Fig. 2 - Illustrating the cosine and sine components of a Fourier transform

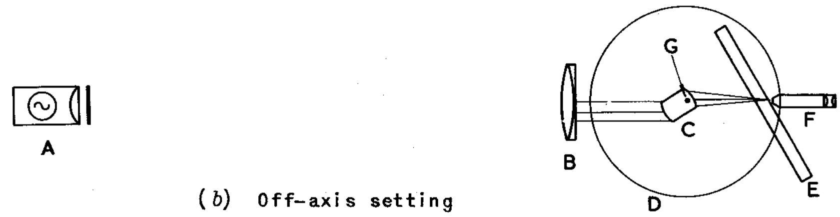
(*a*) cosine component $\int f(x) \cos \omega x . dx$ is the sum of the shaded areas (due regard being paid to sign)

(*b*) sine component $\int f(x) \sin \omega x . dx$ is the sum of the shaded areas (due regard being paid to sign)

*The sine and cosine components are only one special case of the two components required for a Fourier transform. Any two components which have a 90° phase shift will suffice.



(*a*) Axial setting

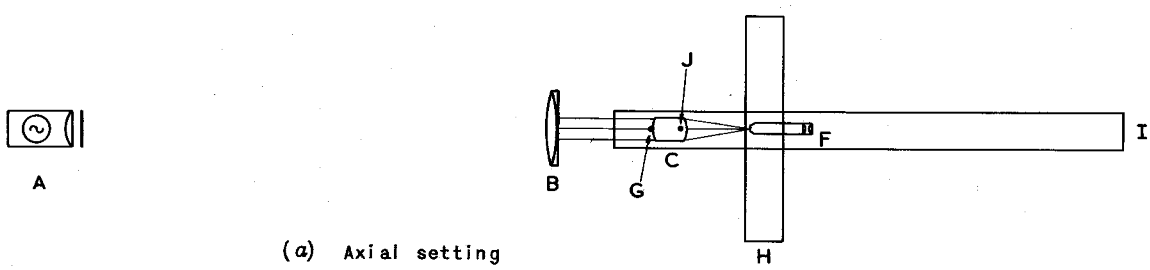


(*b*) Off-axis setting

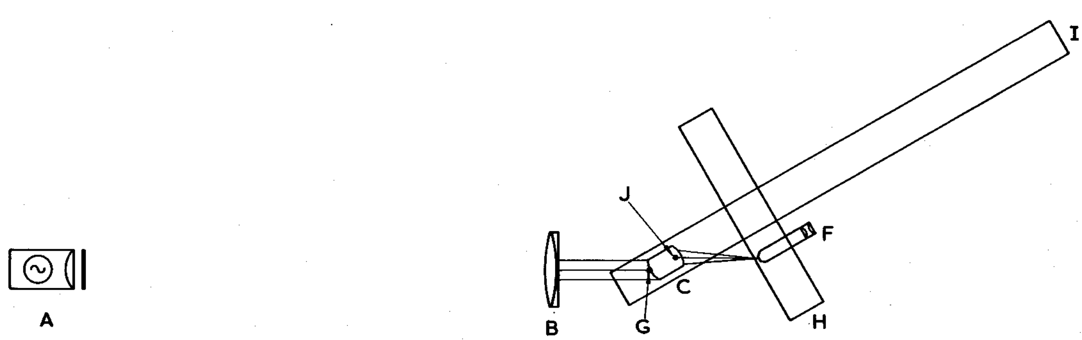
Fig. 3 - Nodal-slide optical bench

A Light source and test object
B Collimator
C Lens under test
D Nodal slide turntable
E Tee-Bar
F Viewing and detecting system
G Axis of rotation of slide turntable (coincident with rear nodal point of lens)

Another type of optical bench may be called the swinging-arm bench; an example of this type was exhibited by Messrs. Precision Tool and Instrument Company at the 1956 Annual Exhibition of the Physical Society. This bench was of large dimensions and appeared to satisfy many of the requirements listed in Section 2. The mode of operation of a swinging-arm bench is illustrated in Figs. 4(a) and 4(b).



(*a*) Axial setting



(*b*) Off-axis setting

Fig. 4 - Swinging-arm optical bench

A Light source and test object
B Collimator
C Lens under test
F Viewing and detecting system
G Axis of rotation of swinging-arm
H Cross-slide
I Swinging-arm
J Rear nodal point of lens

Before deciding whether to continue using a nodal-slide type of bench (but clearly of much larger dimensions than the Mark 1 Taylor Hobson bench) or to use the swinging-arm type, it was necessary to consider the advantages and disadvantages of each type.

The advantages of a nodal-slide type of bench can be summarized as follows:

(i) the image remains located substantially in one position;

(ii) direct measurement of focal length is possible;

(iii) determination of geometrical distortion is straightforward.

The disadvantages are:

(i) rotation about the rear nodal point can cause the front element of a long lens to swing out of the beam of the collimator;

(ii) the bench is not easily adapted for measurements at finite conjugates;

(iii) the bench is less adaptable for measurement of complete optical systems.

The swinging-arm type of bench has the following advantages:

(i) rotation of front element can easily be arranged to coincide with the axis of the swinging arm; hence the front element of the lens under test never swings out of the beam of the collimator and uses substantially the same portion of the beam given by the collimator for axial and off-axis measurements.

(ii) basic simplicity of design means easy adaptation for finite-conjugate working and also testing complete optical systems.

The disadvantages are:

(i) off-axis image has to be located and hence a rapid visual inspection of the whole field is not possible;

(ii) focal length is not directly given;

(iii) geometrical distortion not easily measured.

In view of its greater versatility it was decided to use a swinging-arm type of bench for the new optical bench, although clearly each type of bench has its own particular virtues.

6. DETAILED DESCRIPTION OF THE OPTICAL BENCH

An overall view of the bench is given in Fig. 5. The light source A is a 100 watt tungsten lamp together with a condenser and one sheet of diffusing material. Provision is made for the insertion of neutral filters and colour filters behind the test object which usually takes the form of a thin slit. The lamp house is mounted

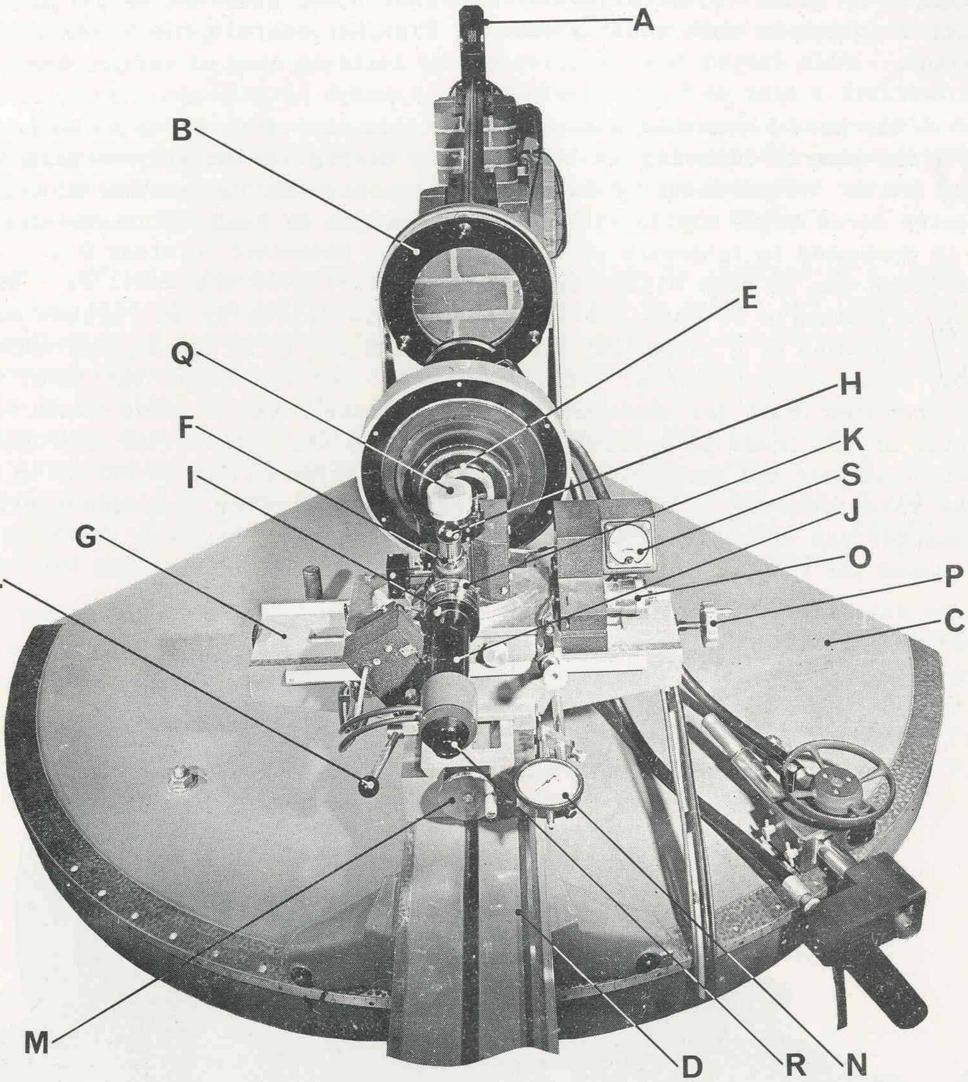


Fig. 5 - Photograph of optical bench

on a two metre optical bench of triangular cross-section. For measurements at infinite conjugate, the test object is positioned at the focus of the 120 in (3·05 m) collimator lens B which is an air-spaced doublet of 8 in (20 cm) diameter. The collimator can be removed by unscrewing the three knurled screws whereupon axial measurements at finite conjugates can be made.*

The collimator bracket is mounted on a large sector-shaped horizontal casting C which carries the swinging arm D upon which is mounted the lens under test E and the image viewing and measuring device F, the latter being mounted on the cross slide G. The lens under test forms an image of the test object slit

*Off-axis measurements at finite conjugates require either the use of a second cross-slide not shown in Fig. 5 or a manual adjustment of the light source distance for each field angle $[\Delta = (1+m)(\sec\theta-1)\,f]$ where Δ = change in distance of test object, f is the focal length, m = magnification and θ = field angle.

which is magnified by a relay lens (8 mm and 4 mm apochromatic microscope objectives are used for this purpose). The magnified image can be viewed through the eyepiece H or measured by means of the sine-wave analyser I and photomultiplier photocell J. The knob K (which is more clearly seen in Fig. 6) controls the phase of the sine-wave plate.

The knob L controls a locking device on the carriage supporting the cross-slide G and coarse focusing is achieved by moving the whole assembly along the sliding arm D. Fine focusing is achieved by rotating the knob M which rotates a micrometer screw of 40 t.p.i. Shifts of focus can be read-off on the dial gauge N which is graduated in intervals of 10 μ and can be estimated to about 2 μ. Centering of the image can be done either by the micrometer O, or the wheel P. The reason for two adjustments is that the micrometer O is driven by an impulse motor when making a recording of a tangential spread function and it is usually convenient to use this for small lateral shifts. The wheel P is used for larger shifts of the image receiving system which are necessary when an off-axis image is being found. Vertical centering of the image is available by rotating Q which lifts the microscope tube, sine-wave analyser and photocell. The photomultiplier output is fed to an amplifier via the potentiometer R. The output from the amplifier operates the recording milliammeter and also the meter S (in series with the recorder) which is conveniently placed for reading during the setting-up of the lens under test.

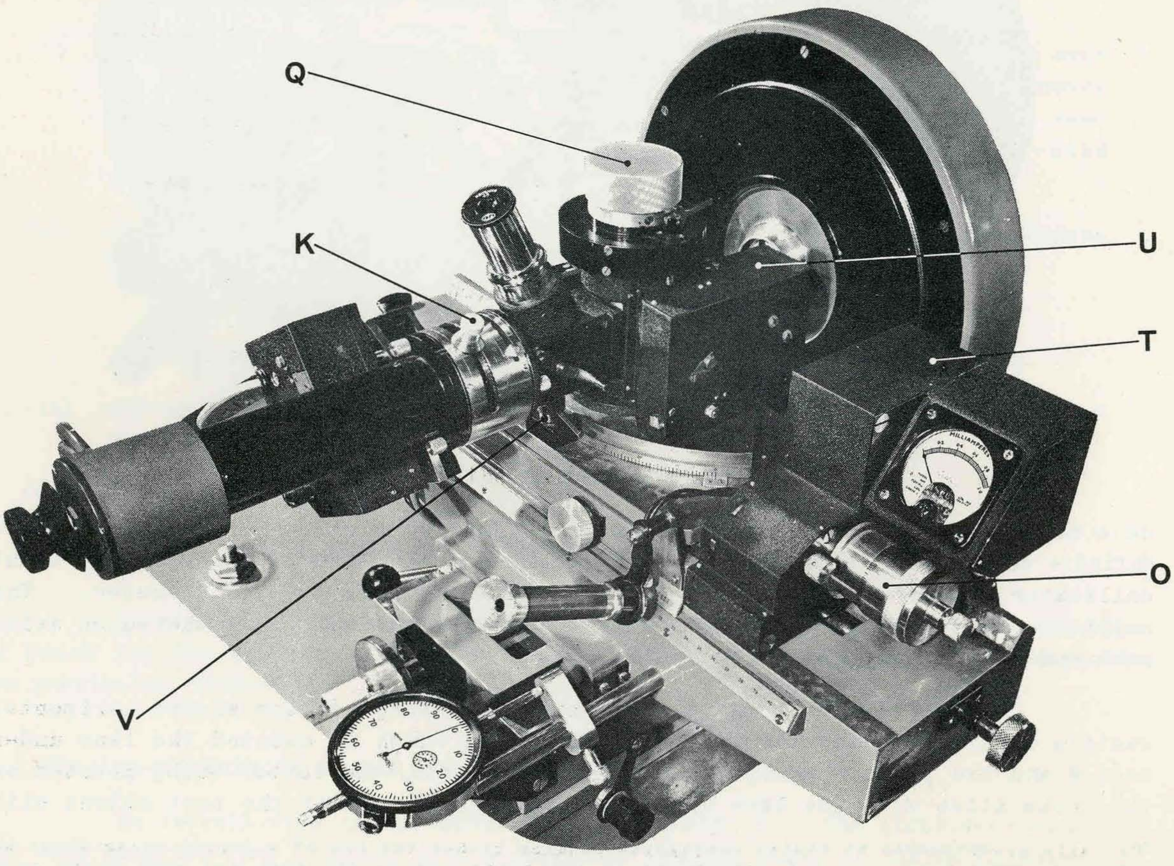


Fig. 6 - Scanning head, sine-wave analyser and cross slide of optical bench

A more detailed view of the receiving and viewing system is shown in Fig. 6. The impulse motor T is used when a tangential spread function is required, as stated above. This drives the micrometer O in steps of 1 μ through a gear-train so that a slow mechanical scanning of the image is performed. For this purpose, the slit in the sine-wave analyser is made parallel to the vertical test object slit. The vertical centering knob Q can also be driven by an impulse motor U so that a sagittal spread function can be recorded. The test object slit and the sine-wave slit are both rotated to a horizontal setting for a sagittal spread function. As with the automatic recording facility on the Taylor Hobson bench,[2] three rates of recording of spread function are available viz. 10, 20 and 40 microns per inch of recording paper.

For off-axis measurements when the swinging arm is inclined at a large angle to the optical axis of the collimator, it is necessary to rotate the image receiving system (consisting of microscope objective sine-wave analyser and photo-multiplier) if the microscope objective is not to restrict the image-forming rays. Facility for doing this is provided by pivoting the sector-shaped plate which supports the image receiving system on a vertical axis a little in front of the front edge of the cross-slide G. The sector-shaped plate is clamped by the small lever V. As an example of the angular field covered without the need to use this facility, a lens with a relative aperture of $f/2$ can be tested up to 30° semi-angular field. Beyond 30° the image receiving system must be rotated towards the incoming light rays.

The output from the photomultiplier is insufficient to operate the recording milliammeter so that a current amplifier with a gain of the order of 10^3 is required. A valve amplifier was used with the Taylor Hobson bench: the corresponding unit in the new optical bench is a transistor amplifier. As a result of this change there has been a marked improvement in the stability of the black level. The amplifier is battery operated with mercury-cadmium cells; its circuit diagram is given in Fig. 7.

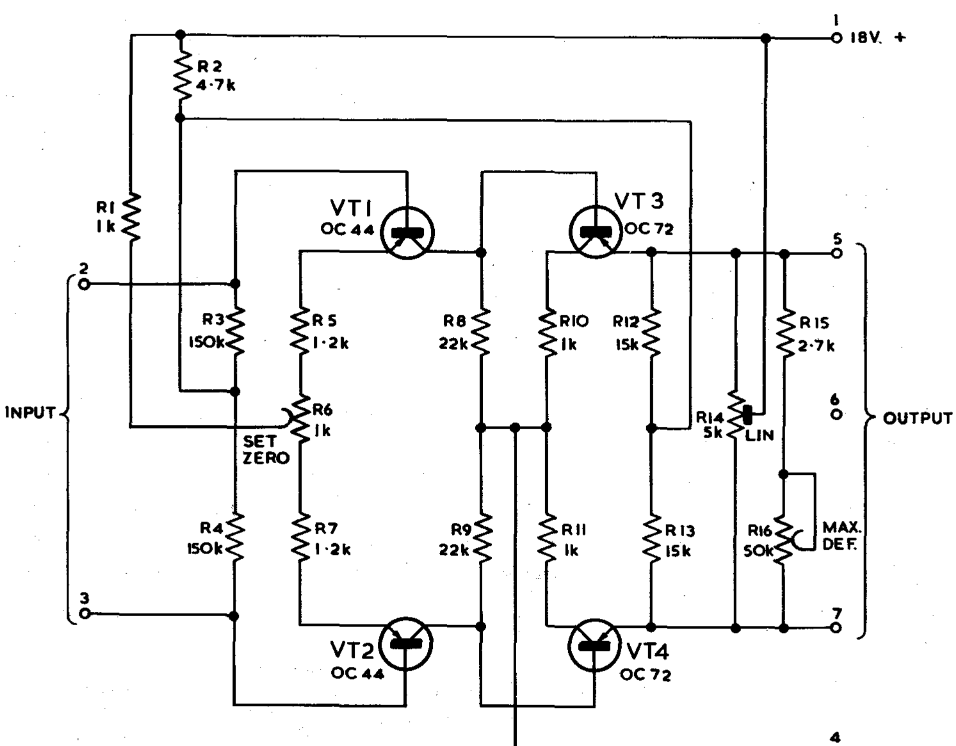


Fig. 7 - Circuit diagram of current amplifier

A point of interest arises in the application of aperture correction for the finite width of the object and scanning slits. In the spread function method, the corrections for both object and scanning slit are in the same sense, i.e. both slits are responsible for a loss of modulation at the higher spatial frequencies. In the case of the sine-wave analyser,* the two corrections are in opposite senses and this makes it possible to achieve a direct result which requires virtually no aperture correction. The mathematical form of the two corrections is not identical, but if the nominal width of the image of the test object slit is made equal to the width of the slit in the sine-wave analyser (as seen through the microscope objective) and provided that this width is less than a quarter of the shortest wavelength tested, then the corrections are self-cancelling to better than half a percent over the range of spatial frequencies investigated.

7. MEASUREMENTS AT FINITE CONJUGATES

A second cross-slide is used when measurements are required at finite conjugates. This cross-slide has its own light source. The same slit assembly is used either for working at infinite or finite conjugates. This assembly has nine slits any of which can be brought to the central, active, position: it is also easy to rotate the slits so that they are either vertical (for tangential modulation transfer functions) or horizontal (for sagittal functions).** The slits were prepared by vacuum evaporation of aluminium on to a glass plate with a wire of appropriate diameter stretched across the glass (and in contact with it). The widths of the slits range from 13½ to 1226 μ. This range is needed so that the nominal image produced by the lens under test shall be about 5 μ. Even so, the range is not as great as would be desirable, e.g. for measurements at unity magnification a slit of 5 μ would be highly desirable. The present practice is to make the necessary aperture correction when the nominal image of the object slit is not 5 μ.

The light housing on the cross slide is arranged to rotate about a vertical axis through the object slit. This was found to be vital for off-axis working; otherwise little or no light flux from the object slit reaches the entrance pupil of the lens under test.

8. PERFORMANCE TESTS

8.1. Sine-Wave Analyser

There are a number of features of the sine-wave analyser which require accurate construction and careful checking in order that the results shall be reliable. The concentricity of rotation of the sine-wave plate needs to be good: some relaxation in mechanical tolerances is obtained by virtue of the fact that the sinusoid is situated in the magnified image plane. If we take 30 c/mm in the primary image plane as the highest spatial frequency measured (in conjunction with an 8 mm apochromatic

*for a mathematical treatment, see the Appendix.

**The measurement of the spread function is limited to tangential and sagittal orientations of the test object. The sine-wave analyser, however, is not restricted to these two orientations since it suffices for the analyser slit to be orthogonal to the test object slit, and the sine-wave plate can be rotated so that it is parallel to the analyser slit at the commencement of a recording.

relay lens), then the smallest wavelength is 33 μ, which becomes 660 μ in the magnified image plane. Any error of centering should certainly be less than one tenth of this figure and preferably better than one twentieth. Examination of this part of the apparatus shows a maximum shift of the order of about 10 μ which is small in terms of the minimum wavelength used.

Another feature of the sine-wave analyser which is essential for accurate results is the correct transmission characteristic of the sine-wave plate. The sine-wave plate was made by an interference technique. Localized fringes formed by a thin wedge in monochromatic light (green 5461 A° Hg line isolated by an Ilford Mercury filter) were photographed and a positive was printed from the negative. The transmission characteristic is shown in Fig. 8. A compromise needs to be effected between the contrast (modulation depth) and accuracy of characteristic. In order to obtain a high contrast a considerable excursion of the photographic transfer curve ("H and D" curve) is used and non-linearity becomes increasingly troublesome; hence a good approximation to a sine-wave is difficult to achieve with high contrast. In the present case, a modulation of about 84 per cent is obtained with a fair approximation to a sine-wave transmission characteristic.

Probably the best way of checking the performance of the sine-wave analyser is to present it with a function (i.e. test object) whose Fourier transform is well known and precisely determined. A slit uniformly illuminated with incoherent light satisfies this requirement and its normalized Fourier transform is the sin $k\nu/k\nu$ function, where ν is the spatial frequency and k is $2\pi b$ for a slit of width $2b$. Two examples of this are given in Fig. 9 where the continuous curves are the mathematical sin $k\nu/k\nu$ functions and the plot points are the measured values. This check serves two purposes, (i) it shows whether the spatial frequency scale (abscissa) is correct by virtue of the location of the zeros, (ii) it checks the shape of the output curve which is dependent mainly on the accuracy of form of the sine-wave plate. Check (i) is independent of check (ii).

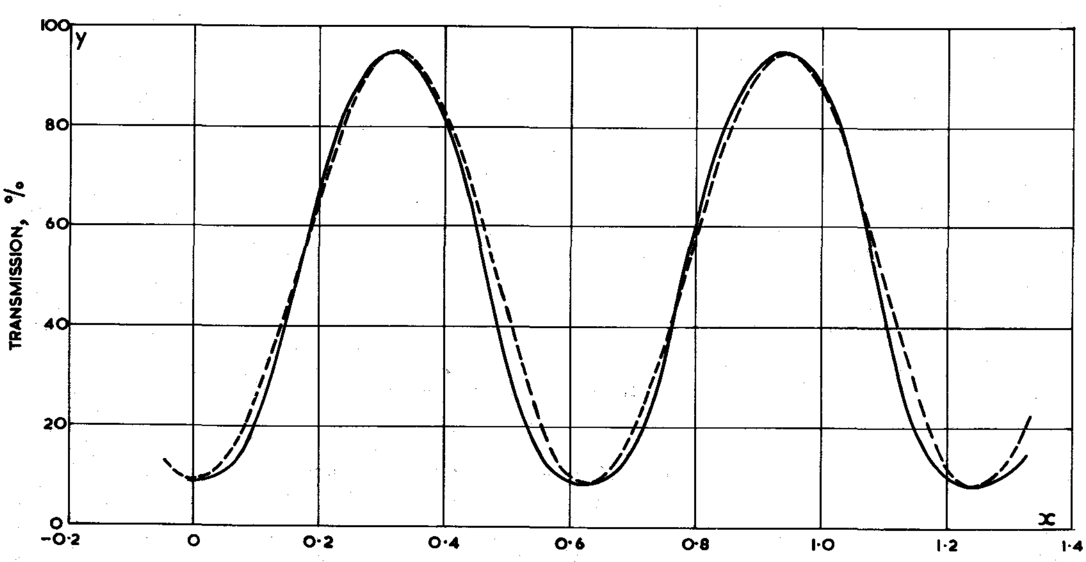


Fig. 8 - Transmission characteristic of the sine-wave grating

——— MEASUREMENT

- - - - - PLOT OF $y = 52 + 43 \sin 2\pi \left(\frac{x - 0{\cdot}164}{0{\cdot}618}\right)$

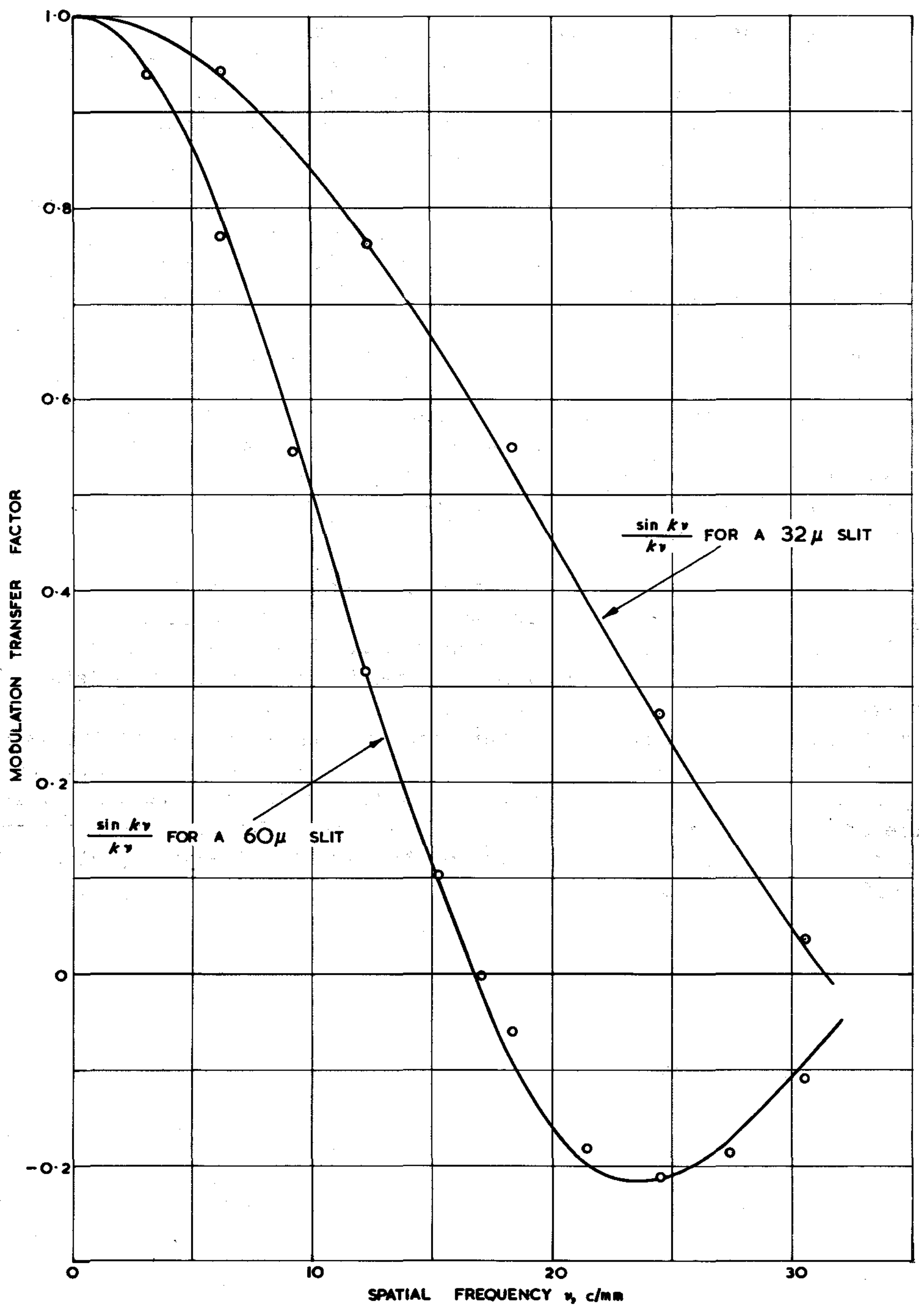


Fig. 9 - Comparison of theoretical and practical results for two rectangular slits

$k = 2\pi b$, WHERE $2b$ = WIDTH OF SLIT.
o o o EXPERIMENTAL RESULTS.
——— THEORETICAL RESULT.

8.2. Comparison of Sine-Wave Analyser Results with Results Obtained by the Spread Function Method

This comparison is most easily shown in graphical form and Figs. 10, 11 and 12 are offered in evidence of the substantial agreement which has been achieved between the two methods. Figs. 10 and 11 relate to axial modulation transfer functions and Fig. 12 relates to an off-axis function. In the case of an image whose spread function is very extensive, the sine-wave analyser can give a slightly favourable answer because its slit has a finite length and the spread-function may extend beyond this. This fact is responsible for the greater modulation transfer factor in the range of spatial frequencies from 0 to 12 c/mm (Fig. 12) when the sine-wave analyser results are compared with those derived from the spread function. This

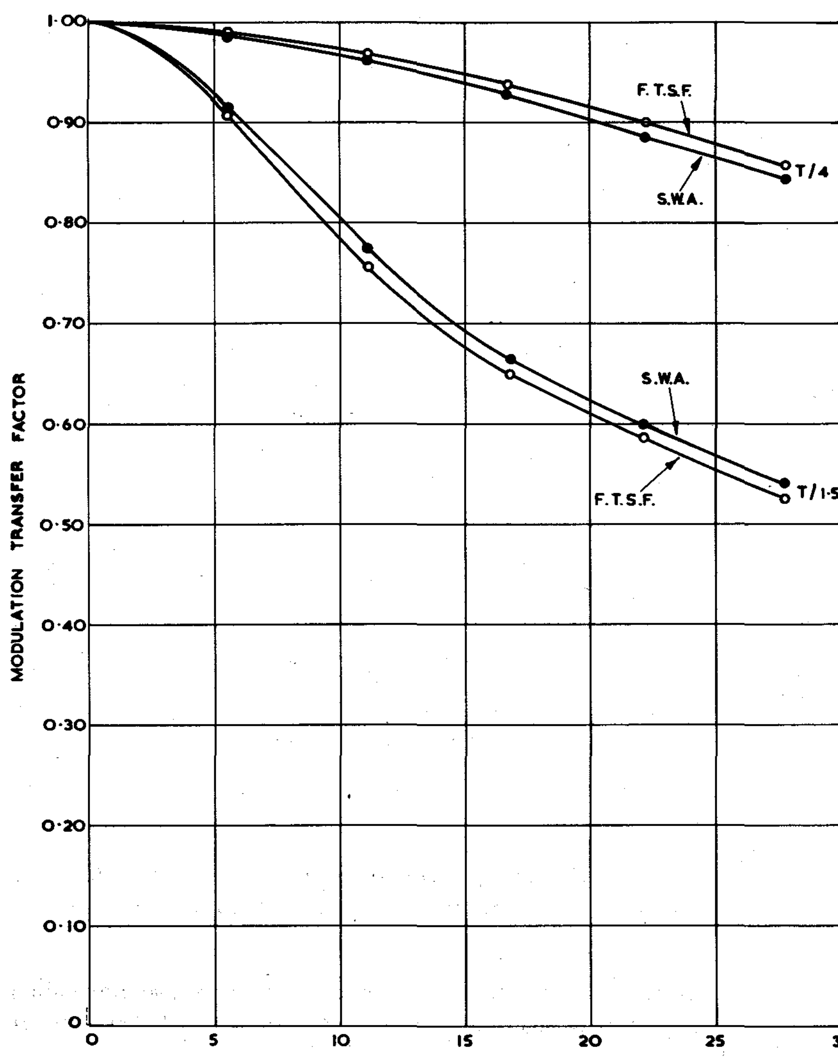


Fig. 10 - Comparison of results for a 5 cm T/1·5 lens: axial image

o———o FOURIER TRANSFORM OF SPREAD FUNCTION.
●———● SINE-WAVE ANALYSER

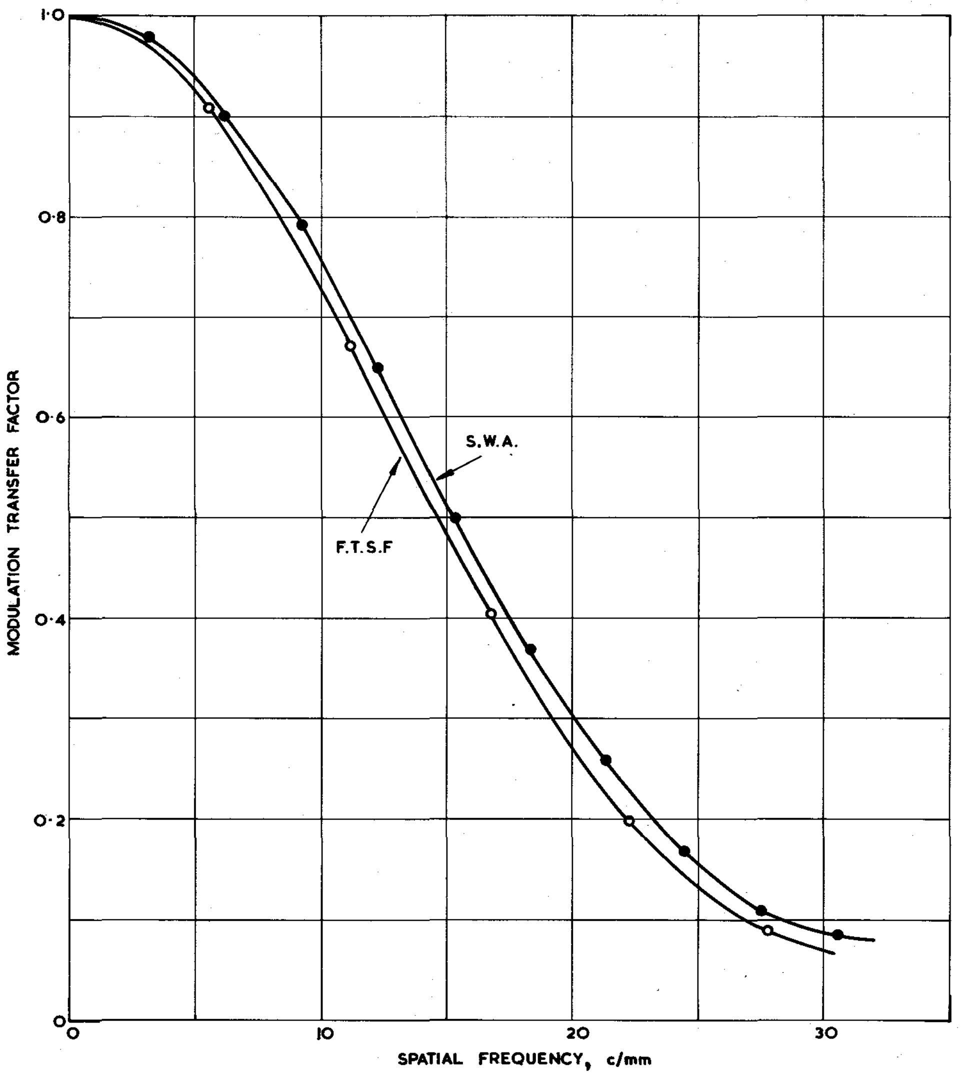


Fig. 11 - Comparison of results for a defocused $1\frac{1}{2}$ in (38 mm) $f/1{\cdot}9$ lens axial image

o———o FOURIER TRANSFORM OF SPREAD FUNCTION.
●———● SINE-WAVE ANALYSER.

limitation of the sine-wave analyser applies only in cases where the quality of the image is relatively poor and well below the standard laid down in the BBC Specification for lenses.[6]

The results given in Figs. 10 and 11 show that the two methods give results which never disagree by more than 3% over the range of spatial frequencies from zero to 30 cycles per mm.

8.3. Modulation Transfer Function of the Microscope Objective

The primary image formed by the lens under test is relayed by a microscope objective on to the plane of the slit. It is essential that the microscope objective

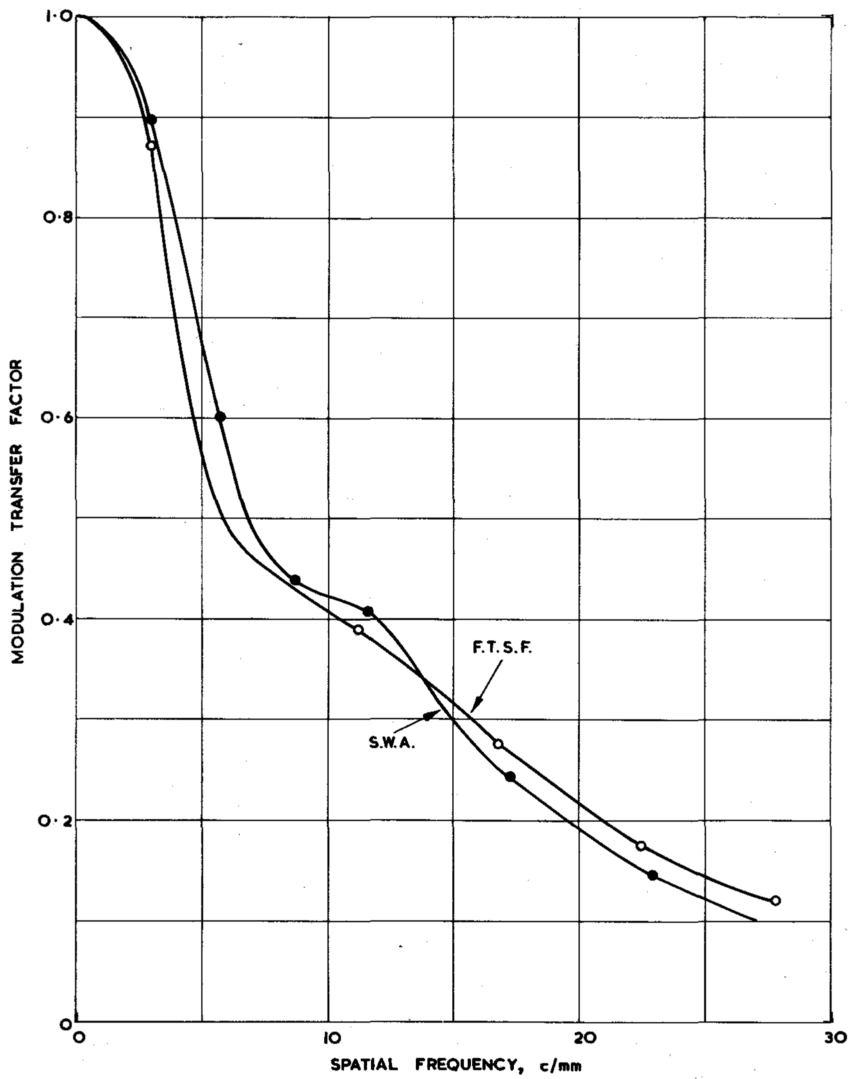


Fig. 12 - Comparison of results of $1\frac{1}{2}$ in (38 mm) $f/1{\cdot}9$ lens at 20° tangential

O———O FOURIER TRANSFORM OF SPREAD FUNCTION.
●———● SINE-WAVE - ANALYSER.

shall make a negligible contribution to the aberrations of the lens under test. The modulation transfer function of the 8 mm apochromat used as a relay lens was measured by determining the spread function produced by a 5 μ slit when imaged by the objective (this measurement was done on the Mark 1 TTH bench). The result is shown in Fig. 13 and it will be observed that up to 30 c/mm the loss in modulation is less than 2%.

In Section 8.1. the test using a slit includes any errors introduced by the microscope relay lens.

8.4. Consistency of Measurements using the Sine-Wave Analyser

The measurements given in Section 8.2. were done by one careful observer. It is of interest to know whether measurements are repeatable and whether different

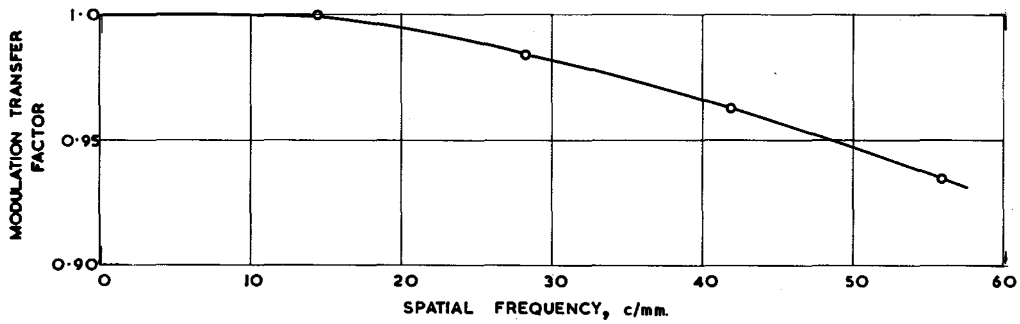


Fig. 13 - Modulation transfer curve of the 8 mm apochromatic objective

workers obtain the same result. To answer the latter question, the modulation transfer function of a defocused 50 mm lens was measured by four workers. The reason for choosing a defocused image is that a steeply descending function is more sensitive to positional experimental errors in the frequency-scale than a monotonic function of high value throughout the range of measurements. The results are given in Table 1.

TABLE 1

SPATIAL FREQUENCY c/mm	MODULATION TRANSFER FACTOR % Worker 1	2	3	4	MEAN VALUE	DIFFERENCES FROM MEAN % Worker 1	2	3	4	STANDARD* DEVIATION σ %
3•05	95•7	94•6	93•5	92•4	94•05	1•65	0•55	-0•55	-1•65	1•42
6•1	77•4	76•4	76•1	73•0	75•72	1•68	0•68	0•38	-2•72	1•90
9•15	53•6	52•6	52•2	49•1	51•88	1•72	0•72	0•32	-2•78	1•94
12•2	31•6	30•5	28•5	27•1	29•42	2•18	1•08	-0•92	-2•32	2•01
15•25	13•2	13•5	12•6	10•4	12•42	0•78	1•08	0•18	-2•02	1•40
18•3	4•3	4•3	5•8	4•8	4•8	-0•5	-0•5	1•0	0	0•71

It will be observed that the maximum standard deviation is about 2% and this holds over the range of spatial frequencies from 6 to 12 c/mm where the function is steeply descending (Fig. 14). It is considered that this represents the upper limit of inaccuracy of measurement (except for the case illustrated in Fig. 12 where the spread function exceeds the aperture of the slit in the sine-wave analyser). This level of accuracy is considered sufficient for most purposes: an improvement can be effected if several measurements are taken and averaged but this is not normally necessary.

*Standard deviation σ is strictly $[\Sigma\,(\Delta x)^2/(n)]^{\frac{1}{2}}$: however, when n is small a better estimate of the standard deviation of the parent population is given by $[\Sigma\,(\Delta x)^2/(n-1)]^{\frac{1}{2}}$ and this formula has been used here. The standard deviation of the mean (standard error) is $\sigma/(n)^{\frac{1}{2}}$ which is half the value quoted in the last column for $n = 4$.

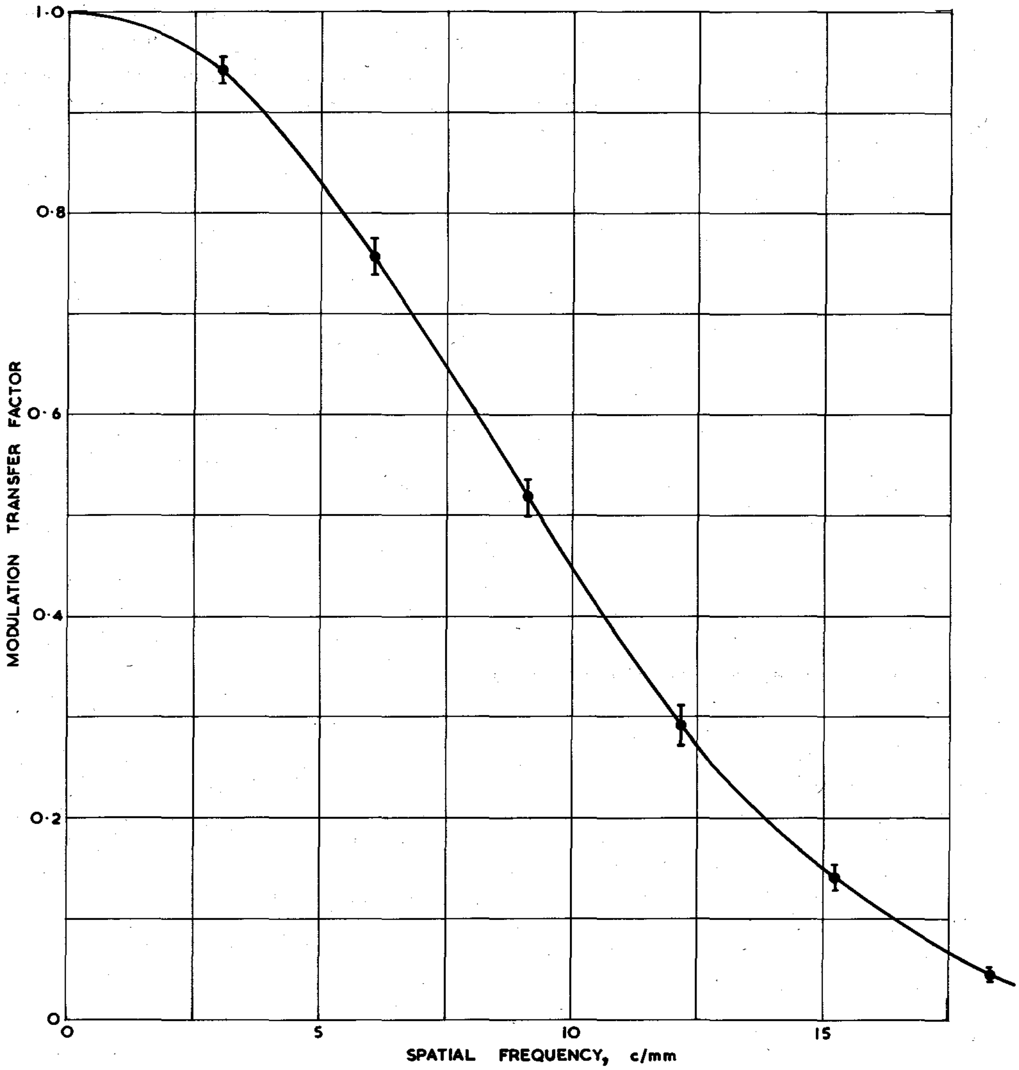


Fig. 14 - Consistency of results from four observers

solid line is the mean
vertical lines at plot points show ± standard deviation.

9. OPERATIONAL EXPERIENCE

The optical bench has now been in use for about two years. During this period a considerable number of lenses and optical systems has been measured. In the matter of fixed focus lenses, the shortest focal length encountered has been that of a 12 mm lens for 8 mm cinematography and the longest, that of a 40 in (1·02 m) lens used with the image orthicon camera. The lens with the greatest angular field has been a 28 mm $f/2$ lens designed for the image orthicon camera (semi-angular field = 35° 6'). The largest zoom lens, which also uses folded optics in the rear conjugate axis was the Varotal III.[7] Other zoom lenses include several with four-to-one zoom ratio and more recently two ten-to-one zoom lenses.[8] So far no lens has been either too large or too small to be mounted and measured.

Multiplex optical systems for vidicon telecine machines and the optical systems of two colour cameras[9] have been accommodated and measurements of the modulation transfer functions have been made. Sufficient space exists for the mounting of these systems and a blank saddle with a plane horizontal top surface has been very useful for mounting these systems with the aid of specially constructed units.

The facility for measurement at finite conjugates has been frequently used and is certainly very valuable in assessing lenses for flying-spot scanners and telerecording film cameras.

10. CONCLUSIONS

Facilities now exist for the fairly rapid measurement of the optical transfer function of all the lenses and optical systems likely to be employed in television. Up to a spatial frequency of 30 c/mm, the standard deviation of the measurements is of the order of 2%. Measurement at finite conjugates can be accomplished with equal facility to those at infinite conjugates. The bench is sufficiently large and versatile to enable complete optical systems to be measured. It is doubtful whether a nodal-slide type of bench would have been suitable for all the lenses and optical systems which have been measured; the choice of a swinging-arm bench appears to have been completely justified.

11. ACKNOWLEDGEMENTS

The design and construction of the optical bench was undertaken by the Precision Tool and Instrument Company. The detailed design of the scanning head and sine-wave analyser was also done by the same company working in close collaboration with the authors.

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APPENDIX

APERTURE CORRECTION REQUIRED BY THE SINE-WAVE ANALYSER

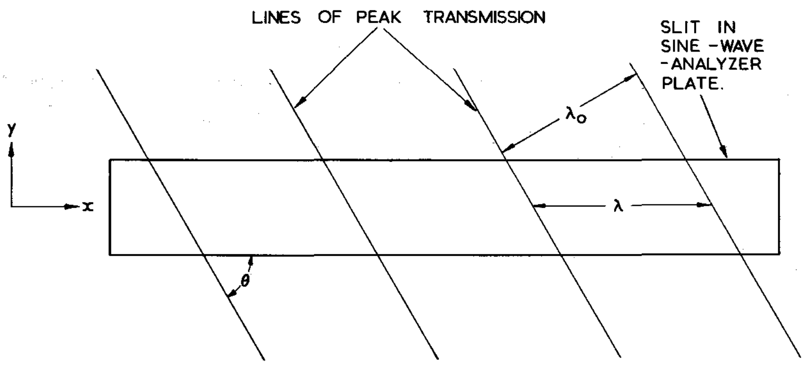

Fig. 15 - Aperture correction required by the sine-wave analyser

X = direction independent variable of Fourier integral

Y = direction of major axis of source slit

Let transmission along centre of slit be given by

$$t = A \cos (2\pi\, x/\lambda + \phi) + C \qquad\qquad A \leqslant C$$

where A/C = modulation λ = effective wavelength at orientation, θ, of sine-wave plate

ϕ = arbitrary phase of grating.

At a displacement of y from centre line, the sine wave is shifted by $-y \cot \theta$

$$\therefore \quad t\,(y) = A \cos \left(2\pi \frac{x+y \cot \theta}{\lambda} + \phi\right) + C$$

If slit is of width $2b$, mean transmission is given by

$$\bar{t} = \frac{1}{2b} \int_{-b}^{b} \left[A \cos \left(2\pi \frac{x+y \cot \theta}{\lambda} + \phi\right) + C \right] dy$$

$$= \frac{\lambda}{2\pi\, b \cot \theta} \left[A \cos (2\pi\, x/\lambda + \phi) \sin \frac{2\pi\, b \cot \theta}{\lambda} \right] + C$$

Thus the original modulation A/C is multiplied by the factor

$$k = \frac{\lambda \tan \theta}{2\pi\, b} \sin \frac{2\pi\, b \cot \theta}{\lambda}$$

and this is independent of the phase angle ϕ

This can be rewritten in terms of the effective spatial frequency $f (= 1/\lambda)$ and the natural spatial frequency of sine-wave grating f_0 $(= 1/\lambda_0)$

$$k = \frac{\sin \{2\pi\ b\ (f_0^2 - f^2)^{\frac{1}{2}}\}}{2\pi\ b\ (f_0^2 - f^2)^{\frac{1}{2}}}$$

Note that when $f = 0$ $\quad k = \dfrac{\sin 2\pi\ b\ f_0}{2\pi\ b\ f_0}$

when $f = f_0$ $k = 1$

It will thus be seen that the variation of k with frequency is in the opposite sense to the spectrum of a thin slit.

A thin slit of width $2b$ has a spectrum proportional to $\dfrac{\sin 2\pi\ b\ f}{2\pi\ b\ f}$

The combined effect of two slits at right angles is thus

$$\frac{\sin \{2\pi\ b\ (f_0^2 - f^2)^{\frac{1}{2}}\}}{2\pi\ b\ (f_0^2 - f^2)^{\frac{1}{2}}} \times \frac{\sin (2\pi\ b\ f)}{2\pi\ b\ f}$$

When $2b = \lambda_0/4$ the product given above is constant to about 0·1% over the frequency range $f = 0$ to $f = f_0$

A narrower slit (e.g. $2b = \lambda_0/6$) does not give as good constancy of product over the range $f = 0$ to $f = f_0$ and in fact varies by about 0·5%.

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